Investigation of GAM zonal flows in the TEXTOR tokamak

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Introduction

It is well known that the zonal flow (ZF) can extract energy from ambient turbulence due to reverse energy cascade and meanwhile reduces radial transport due to tilting turbulent eddies by the ZF radial electric field. In toroidal plasmas, two types of ZFs are expected: the low-frequency ZF and the high-frequency geodesic acoustic mode (GAM) [1]. It has been recently reported that the low-frequency ZFs are excited at TEXTOR during the biasing H-mode, confirmed by long-distance correlations in potential fluctuations [2]. In this paper, we present the results of the GAM zonal flows observed in ohmic discharges at TEXTOR. Moreover, the reduction effects of the TEXTOR-DED (Dynamic Ergodic Divertor) on the GAMs have also been reported.

Experimental setup

The experiment was conducted on the TEXTOR tokamak with major radius R = 175 cm and minor radius a = 48 cm. Ohmically heated deuterium discharges were employed with typical plasma current I_p = 250 kA, toroidal magnetic field B_T = 2.25 T, line average density $\langle n_e \rangle = (1-3) \times 10^{19} m^{-3}$ and safety factor at the limiter position $q_a \approx 6$. Two Langmuir probe arrays, one stationary and the other fast reciprocating, were equipped to measure the floating potential (ϕ_{fl}) and ion saturation current ($\propto n_e$) and their fluctuations. Both probe systems were installed on the outer equatorial plane (low-field side), but at two toroidally opposite locations. The fluctuation data were sampled at a rate of 500 kHz for 2 s duration. Note that in this study such a long sampling time is necessary for the evaluation of bicoherence of the three-wave coupling of GAMs to reduce the statistical uncertainty. Apart from this, several other data analysis techniques, like Hilbert transform and waiting-time distributions of burst events have also been used.

Results and discussion

The typical power spectrum of floating potential fluctuations ($\tilde{\phi}_{fl}$) measured in the plasma edge is shown in the Fig. 1(a). A significant peak appears at the frequency around 10 kHz, which is consistent with the theoretical prediction of the GAM frequency $f_{GAM} = \sqrt{2(T_e + T_i)/M_i}/2\pi R \approx$

$10kHz$ [1] . In our experiment, the dependence of f_{GAM} on the local temperature ($T_e \approx T_i$) has been verified in discharges with different T_e.

To investigate the toroidal and poloidal structure of the GAM zonal flow, we have measured the long-distance toroidal ($\approx 7m$) and poloidal ($\approx 1.5cm$) cross-correlation in the $\tilde{\phi}_{fl}$ signals, defined as $C_{xy}(\tau) = \langle [x(t+\tau) - \bar{x}][y(t) - \bar{y}] \rangle / \sqrt{\langle [x(t) - \bar{x}]^2 \rangle \langle [y(t) - \bar{y}]^2 \rangle}$, where τ is the time lag. The results are presented in Figs. 1(b) and (c). The nearly zero-delay time in the $C_{xy}(\tau)$ function clearly indicates that the GAM oscillation in $\tilde{\phi}_{fl}$ is in-phase in both toroidal and poloidal directions and hence its structure is uniform (m=n=0), as predicted by the theory [1].

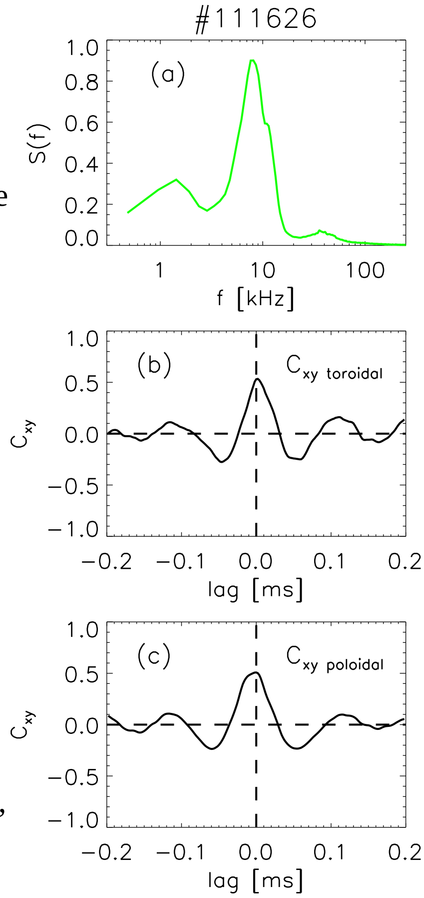

Figure 1: *(a) Power spectrum of ϕ_{fl} fluctuations, ($\tilde{\phi}_{fl}$) measured at the edge of TEXTOR (r/a = 0.96). The cross-correlations of $\tilde{\phi}_{fl}$ measured by two (b) toroidally and (c) poloidally separated probe pins.*

For detecting the nonlinear three-wave interactions among the GAMs and other background turbulence, we have computed the squared bi-spectrum of fluctuations, which is defined as $b^2{}_{\alpha\beta\gamma}(k,l) = \left| \frac{1}{M} \sum_{i=1}^{M} \alpha_k^i \beta_l^i \gamma_{k+l}^i \right|^2 / ([\frac{1}{M} \sum_{i=1}^{M} \left| \alpha_k^i \beta_l^i \right|^2][\frac{1}{M} \sum_{i=1}^{M} \left| \gamma_{k+l}^i \right|^2])$ [3], where α_k means the k komponent of FFT spectrum for signal α. The case of $\alpha = \beta = \gamma$ pertains auto-bicoherence while the others for cross-bicoherence. It is found that auto-bicoherence of $\tilde{\phi}_{fl}$ is stronger than that of $\tilde{n}_e$ and also comparable to cross-bicoherence between $\tilde{\phi}_{fl}$ and $\tilde{n}_e$. Fig. 2(a) presents the surface-plot of squared auto-bicoherence $\hat{b}^2_{\phi_{fl}\phi_{fl}\phi_{fl}}(f_1, f_2)$ of $\tilde{\phi}_{fl}$, ensemble averaged over $M = 1650$ realizations. One can see many substantial peaks in the $f_1 - f_2$ plane. The coupling feature can be more clearly seen in the contour-plot in Fig. 2(b), where the bicoherence exhibits larger values along $f_2 = -f_1 \pm 10kHz$ and at $\pm 10kHz$ lines. Fig. 2(c) shows the summed bispectrum as a function of $f_3 = f_2 + f_1$. The apparent peak at $10kHz$ is clearly visible in the total bicoherence. The peaked value of total bicoherence ~ 0.01 is much higher than the statistical uncertainty $= 1/M \approx 6 \times 10^{-4}$. This peak indicates strong nonlinear interactions between the GAM and ambient turbulence. From the summed bicoherence it can be seen that the value of total bicoherence at other frequencies than $10kHz$ is also larger than the statistical uncertainty.

This means that the nonlinear interaction occurs also among other frequencies in the ambient turbulence.

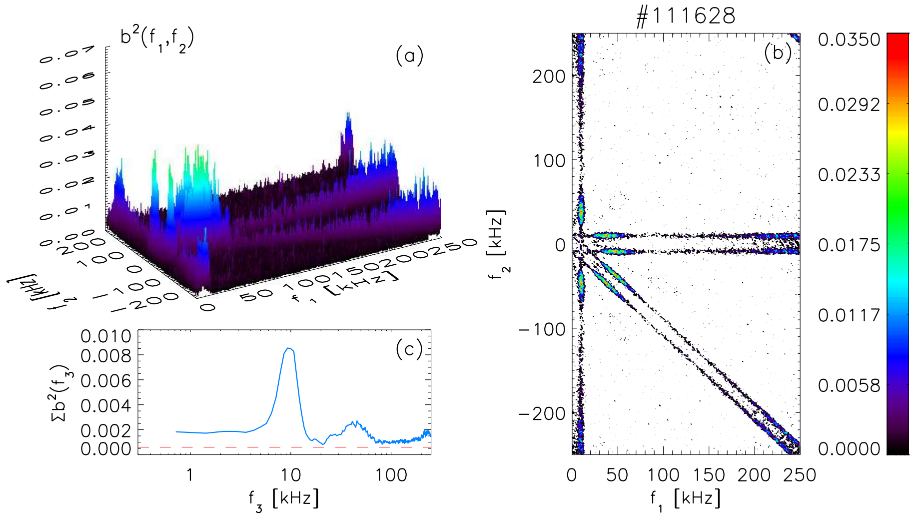

Figure 2: *Squared auto-bicoherence* $\hat{b}^2_{\phi_{fl}\phi_{fl}\phi_{fl}}(f_1,f_2)$ *(a) surface-plot and (b) contour-plot. (c) the summed squared bicoherence* $\Sigma\hat{b}^2_{\phi_{fl}\phi_{fl}\phi_{fl}}(f_3)$ *of* $\tilde{\phi}_{fl}$. *The red dashed line shows the value of statistical uncertainty for 1650 ensembles.*

The next tool to study the nonlinear interaction between the GAM and background turbulence is the envelope analysis technique.

Fig. 3(a) plots the GAM oscillation of $\tilde{\phi}_{fl}$, which is band-pass-filtered in the frequency range of 8-12 *kHz*. Drawn in Fig. 3(b) is the high frequency fluctuations of floating potential in the range 40-60 *kHz*. The green line shows the envelope of the signal, calculated with Hilbert transformation. The results clearly show that the ambient turbulence is modulated at frequency close to the GAM. Therefore, the intrinsic nonlinear interaction exists between the GAM and background turbulence. To investigate the possible

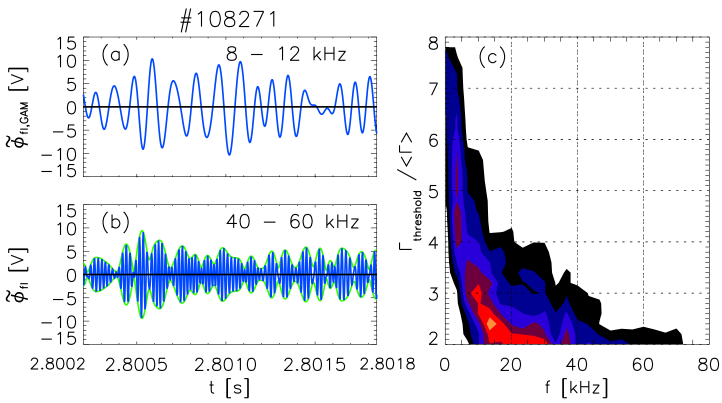

Figure 3: *Modulation of turbulence and particle flux by GAM frequency ≈10 kHz. (a)* $\tilde{\phi}_{fl}$ *of GAM oscillation, band-pass filtered in the frequency range of 8-12 kHz. (b)* $\tilde{\phi}_{fl}$ *of ambient turbulence in the range of 40-60 kHz. The green line shows the envelope of ambient turbulence. (c) histogram of temporal intervals of intermittent events in the turbulent particle flux, discriminated by various thresholds on burst magnitudes.*

impact of the GAM on turbulent transport, we calculated the turbulent particle flux by $\Gamma \sim \langle \tilde{I}_{sat}\tilde{E}_{\theta} \rangle$, where $\tilde{E}_{\theta}$ and $\tilde{I}_{sat}$ is the fluctuations of poloidal electric field and ion saturation current. The signal of Γ is intermittent and the time interval of intermittent events varies when choosing different burst amplitudes. Fig. 3(c) depicts histogramms of burst events as a function of burst frequency, f=1/temporary intervals. The vertical axis is the threshold value selected in the flux amplitude (normalised to the averaged value). In the figure one can see a peak around 10kHz, indicating that the local turbulence flux is also modulated at the GAM frequency.

In this work, the influence of TEXTOR-DED (Dynamic Ergodic Divertor) on the GAM has also been studied. With DED, the resonant magnetic perturbation (RMP) imposes damping effects on GAM magnitudes and their nonlinear interaction with ambient turbulence. In Fig. 4(a), the total bicoherence of $\tilde{\phi}_{fl}$, calculated under different DED configurations (m/n = 6/2 and 3/1), are presented. In both 6/2 and 3/1 modes, with increasing DED current (I_{DED}) the total bicoherence is gradually suppressed. The results imply a significant impact of the magnetic topology on the GAM zonal flows.

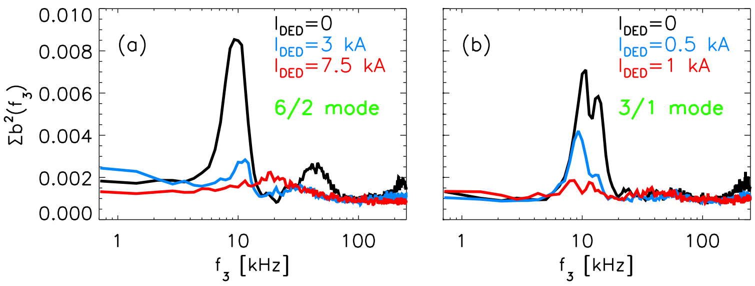

Figure 4: *The summed squared bicoherence* $\Sigma\hat{b}^2_{\phi_{fl}\phi_{fl}\phi_{fl}}(f_3)$ *in different DED modes (a) 6/2 and (b) 3/1 with different DED currents.*

Conclusion

In conclusion, the GAM zonal flows have been studied at TEXTOR. The GAM of $\tilde{\phi}_{fl}$ displays poloidal and toroidal symmetric structure with frequencies proportional to the sound speed. The auto-bicoherence of $\tilde{\phi}_{fl}$ shows strong nonlinear interaction between the GAM oscillation and ambient fluctuations. Such a strong interaction has also been confirmed by strong amplitude modulation of the ambient turbulence and the particle flux by the GAM frequency. During the DED experiment, the GAM and its nonlinear coupling with ambient turbulence are found to be reduced, suggesting a significant impact of the magnetic topology on the GAM zonal flows.

References

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